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Most of the objectives of this research project have been achieved. In this tirst phase of the AFOSR grant (1 October 1 998 - 30 September 2002), the principal investigator and his students have developed a 2-I) unsteady compressible viscous magnetohydrodynamic code designated MI-ID2D which has been validated fbr 2-D internal and external flow& The code solves the coupled MI-ID equations (mass. momentum and energy equations of fluid flow including MHD effects (Lorentz force and Joule heating), magnetic induction equations and Maxwcll cquations) and includes an equilibrium air model for real gas effects, a finite-rate chemical kinetics model for dissociated air, several electrical conductivity models and a bi-temperature model. 'I-his code has been employed to investigate the concept of supersonic drag and heat transfer reduction by modification/dissipation of shock waves in the presence of strong magnetic fields. A series of numerical experiments for blunt body flows and scramjet inlet flow fields have been conducted by varying the Mach number, Reynolds number, degree of ionization of the air plasma and the intensity of the magnetic field to understand the physics of the phenomena and its potential for supersonic drag reduction in practical applications.

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NUMERICAL SIMULATION OF COMPRESSIBLE VISCOUS MAGNETO-HYDRODYNAMICS EQUATIONS WITH CHEMICAL KINETICS

AFOSR GRANT NO. F49620-99-1-0005

Ramesh K. Agarwal

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Objective

The objective of this research project is to provide physical understanding and quantitative prediction of the effect of magnetic field on hypersonic flow of a slightly ionized gas with finite-rate chemistry via numerical simulation. The objective has been achieved by developing a two-dimensional computational code that solves the MHD equations (mass, momentum and energy equations of fluid flow including Lorentz force and Joule heating, magnetic induction equations and Maxwell equations) and includes several electrical conductivity models, an equilibrium air model and a finite-rate chemical kinetics model, and a one-equation turbulence model. The code has been validated by computing some benchmark MHD flow problems, for example flow in a magnetic shock tube, shock structure in the presence of magnetic field, Hartmann-Poiseuille flow, MHD boundary layer on a flat plate, etc. The validated code then is employed to compute the hypersonic flow of a weakly ionized air plasma past a blunt body and in a scramjet inlet to investigate the possibility of drag reduction by the application of a strong magnetic field.

Status of Effort

Most of the objectives of this research project have been achieved. In this first phase of the AFOSR grant (1 October 1998 – 30 September 2002), the principal investigator and his students have developed a 2-D unsteady compressible viscous magnetohydrodynamic code designated MHD2D which has been validated for 2-D internal and external flows. The code solves the coupled MHD equations (mass, momentum and energy equations of fluid flow including MHD effects (Lorentz force and Joule heating), magnetic induction equations and Maxwell equations) and includes an equilibrium air model for real gas effects, a finite-rate chemical kinetics model for dissociated air, several electrical conductivity models and a bi-temperature model. This code has been employed to investigate the concept of supersonic drag and heat transfer reduction by modification/dissipation of shock waves in the presence of strong magnetic fields. A series of numerical experiments for blunt body flows and scramjet inlet flow fields have been conducted by varying the Mach number, Reynolds number, degree of ionization of the air plasma and the intensity of the magnetic field to understand the physics of the phenomena and its potential for supersonic drag reduction in practical applications. In addition, the numerical simulations have been performed to evaluate the "MHD bypass energy concept" which essentially involves magnetogasdynamic extraction of energy

from the flow in the inlet to slow down the flow at the entrance of the combustor. The extracted energy can then be used for other onboard functions or for accelerating the flow exiting the combustor thereby providing additional thrust. The inlet, the MHD generator employed for extraction of energy, the combustor, and the MHD accelerator constitute the so called "MHD bypass propulsion" system which has the potential to make the high speed ramjet engines feasible. In these calculations, a seven species chemical kinetics model for dissociated air was employed. Several fundamental studies on wave propagation and shock propagation in a weakly ionized air plasma have also been conducted.

In addition, a baseline three-dimensional compressible viscous MHD code designated MHD3D has been developed which solves the mass, momentum and energy equations of fluid flow including the Lorentz force and Joule heating and the magnetic induction equations. This code has been validated by computing the flow in a 3-D square duct; benchmark computations are available for this test case for comparison purpose. Effort is also currently underway to include zero-, one- and two-equation $k-\varepsilon$ turbulence model in the 2-D code MHD2D.

Accomplishments and Their Relevance to the Air Force Mission

The aero-thermal problems associated with hypersonic flight vehicles and associated air-breathing propulsion systems have led to the revival of research in the use of magnetohydrodynamic (MHD) flow control as a possible solution. The formation of weakly ionized—hence conducting—plasmas due to the high temperatures in hypersonic flow fields has opened up the possibility of using electromagnetic fields to reduce drag, skin-friction and heat-transfer loads. Recent interest in this area by the U.S. Air Force has been sparked primarily by plasma flow control studies associated with the Russian experimental vehicle concept AJAX where the shock structure in a weakly ionized plasma has been shown to be weaker than that in a non-ionized gas at the same temperature. Several hypotheses have been advanced to account for the observed non-trivial dynamic properties of a gas discharge plasma that can be divided into two groups. The first group is based on the assumption that the weak disturbances propagate in the plasma at a velocity greater than the thermal sound velocity. The second group, (the "energy hypothesis"), rests on the assumption that the energy is released in the shock layer after the shock front, i.e., either the release of energy is concentrated in the molecular degrees of freedom or it is a consequence of current flowing in the shock wave.

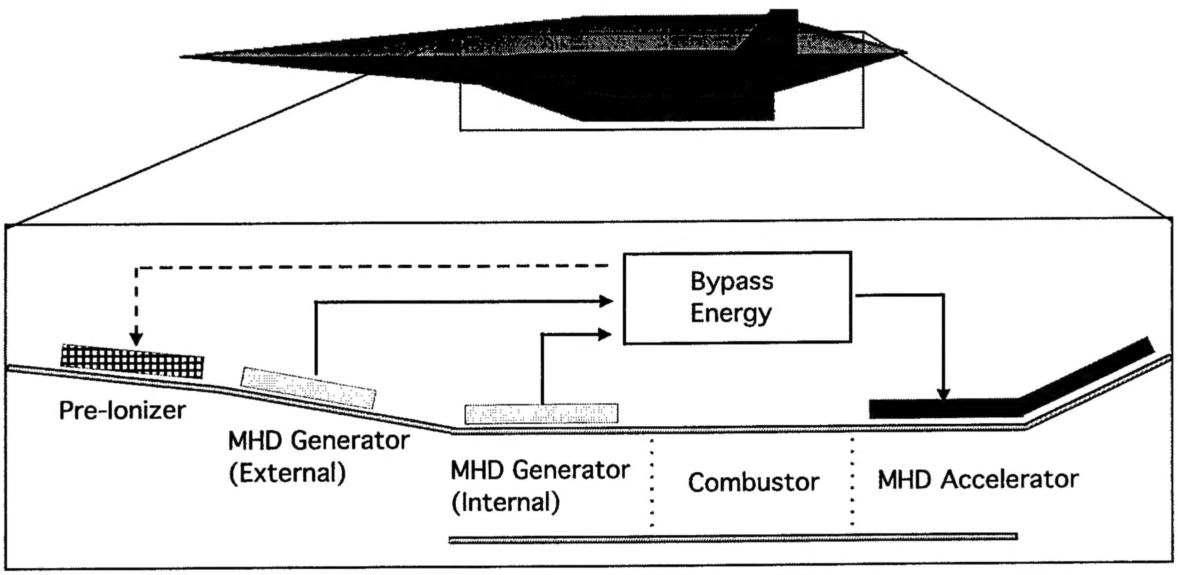

Figure 1. The MHD Bypass Propulsion System

Furthermore, as the Air Force's "AJAX" effort to investigate the possibility of supersonic drag reduction by dissipation/elimination of shock waves using MHD flow control has progressed, recent interest has converged on the formulation of a MHD Bypass Propulsion System (Figure 1) for air-breathing engines to assess the feasibility of high-speed scramjet and ramjet/RBCC engines. In this concept, MHD generators are used to provide additional compression with lower losses both externally (fore-body compression surfaces) and internally, at inlets ahead of the combustion chamber. In the latter case, the conversion of flow enthalpy to electromagnetic energy allows for the temperature rise in a decelerating inlet flow field to be controlled, thus allowing a higher M_∞ to be flown for the same burner temperature limit. Thus, the Mach number at the combustor entrance can be reduced and ramjet operations can be sustained to higher M_∞. The energy extracted in the MHD generator is used to power MHD accelerator downstream of the combustor, and if needed, to power the pre-ionizers. These ionizers may be needed to create the necessary conductivity in the flow if the natural flow conductance is not sufficient to sustain the required degree of MHD interactions. The external MHD generator can also be used to regulate mass flow into the inlets.

The key accomplishment of this research project has been the development of a validated two-dimensional unsteady compressible viscous MHD code with advanced physical models (electrical conductivity models, an equilibrium air model, a 7-species chemical kinetics model for dissociated air, and a bi-temperature model) that has been employed to investigate these MHD control concepts of interest to the Air Force. The computations of hypersonic flow of a weakly ionized air plasma past a blunt body and in a scramjet inlet indicate the possibility of supersonic drag reduction due to modification/dissipation of shock waves as well as enhanced total pressure recovery in an inlet. Development of advanced numerical simulation tools is critical both in understanding the complex physics of these flow as well as for evaluation of "MHD control concepts" when they are applied to real three-dimensional configurations.

Personnel Supported

1. Dr. Prasanta Deb – Postdoctoral Research Associate at Wichita State University (WSU)
2. Mr. Justin Augustinus – Graduate Research Assistant at WSU (Completed M.S. thesis titled, "Numerical Solution of Ideal MHD Equations for a Symmetric Blunt Body at Hypersonic Speeds.")
3. Mr. S. Harada – Graduate Research Assistant at WSU (Completed M.S. thesis titled, "A Fourth-Order modified Runge-Kutta Scheme with TVD Limiters for the Ideal MHD Equations.")
4. Mr. Heru Reksoprodjo – Graduate Research Assistant at WSU (Completed all requirements towards doctoral degree, expected graduation date: Spring 2002)
5. Ms. Yan Tan – Graduate Research Assistant at Washington University (WUSTL)

Refereed Publications

- Agarwal, R. K. and Deb, P., "Numerical Simulation of MHD Effects on Hypersonic Flow of a Weakly Ionized Gas in an Inlet," in *Frontiers of Computational Fluid Dynamics 2002*, D. A. Caughey and M. M. Hafez, Editors, World Scientific, pp. 243-263, 2002.
- Agarwal, R. K. and Gupta, A., "Numerical Investigation of Magnetohydrodynamic Effects in Real Gas Flows," in *Computational Fluid Dynamics for the 21st Century*, K. Morinishi and M. Hafez, Editors, 2001.
- Gupta, A. and Agarwal, R. K., "Numerical Investigation of Real Gas Effects on Magnetohydrodynamic Hypersonic Flows," AIAA Paper 2001-0199, 2001. (accepted for publication in *AIAA J.*)
- Deb, P. and Agarwal, R. K., "A Performance Study of MHD Bypass Scramjet Inlets with Chemical Non-Equilibrium," AIAA Paper 2001-2872, 2001. (submitted for publication in *AIAA J.*)
- Agarwal, R. K., Augustinus, J. and Halt, D. W., "A Comparative Study of Advection Upwind Split (AUSM) and Wave/Particle Split (WPS) Schemes for Fluid and MHD Flows," AIAA Paper 99-3613, accepted for publication in *Int. J. of Computational Fluid Dynamics*, 2001.
- Agarwal, R. K. and Augustinus, J., "A Characteristics Based Box Scheme for Compressible Eight-Wave Structure Ideal MHD Equations," *Computational Fluid Dynamics Journal*, Vol. 8, No. 2, pp. 170-177, July 1999.

Interactions/Transitions

Participation/presentations at meetings, conferences, seminars, etc. (June 2000 – June 2002)

- Deb, P. and Agarwal, R. K., "Numerical Solution of compressible Viscous MHD Equations with Chemical Kinetics," AIAA Paper 2002-0203, AIAA 40th Aerospace Sciences Meeting and Exhibit, Reno, NV, 14-17 Jan 2002.

- Agarwal, R. K. and Deb, P., "Numerical Simulation of Compressible Viscous Magnetohydrodynamics Flows with Chemical Kinetics," Proc. of ECCOMASS CFD 2001, University of Wales at Swansea, U.K., 4 – 7 September 2001.
- Deb, P. and Agarwal, R. K., "A Performance Study of MHD Bypass Scramjet Inlets with Chemical Non-Equilibrium," AIAA Paper 2001-2872, AIAA 32nd Plasma Dynamics and Lasers Conference, Anaheim, CA, 11-14 June 2001.
- Deb, P. and Agarwal, R. K., "Numerical Study of MHD-Bypass Scramjet Inlets," AIAA Paper 2001-0794, 39th Aerospace Sciences Meeting and Exhibit, Reno, NV, 8-11 January 2001.
- Gupta, A. and Agarwal, R. K., "Numerical Investigation of Real Gas Effects on Magnetohydrodynamic Hypersonic Flows," AIAA Paper 2001-0199, 39th Aerospace Sciences Meeting, Reno, NV, 8-11 January 2001.
- Agarwal, R. K. and Gupta, A. (invited) "Numerical Investigation of Magnetohydrodynamic Effects in Real Gas Flows," presented at the symposium in honor of Professor Satofuka's 60th Birthday, Kyoto, Japan, 15-17 July 2000.
- Agarwal, R. K., "A Lattice Boltzmann Method for Simulation of Magnetohydrodynamic Flows," presented at the First International Conference on Computational Fluid Dynamics, Kyoto, Japan, 10-14 July 2000.
- Agarwal, R. K. and Deb, P. (invited) "Numerical Simulation of MHD Effects on Hypersonic Flow of a Weakly Ionized Gas in an Inlet," presented at the symposium in honor of Prof. MacCormack's 60th Birthday, Half Moon Bay, CA, June 2000.
- Deb, P. and Agarwal, R. K., "Numerical Simulation of Compressible Viscous MHD Flows with a Bi-Temperature Model for Reducing Supersonic Drag of Blunt Bodies and Scramjet Inlets," AIAA Paper 2000-2419, 31st AIAA Plasmadynamics and Lasers Conference, Denver, CO, 19-22 June 2000.

Honors and Awards

(a) Received during the grant period:
- AIAA Sustained Service Award (2002)
- ASME Fluids Engineering Award (2001)

(b) Lifetime Achievement Honors:
- Fellow, Royal Aeronautical Society
- Fellow, American Association for Advancement of Science (AAAS)
- Fellow, American Institute of Aeronautics and Astronautics (AIAA)
- Fellow, American Society of Mechanical Engineers (ASME)
- Fellow, Society of Manufacturing Engineers (SME)
- Fellow, Society of Automotive Engineers (SAE)
- Senior member, Institute of Electrical and Electronic Engineers (IEEE)
- McDonnell Douglas Fellow (1991-1994)
- AIAA Distinguished Lecturer (1996-1999)
- ASME Distinguished Lecturer (1994-1997)
- IEEE Distinguished Lecturer (1994-2002)
- American Physical Society Forum on Industrial and Applied Physics Distinguished Speaker (1995-present)

- University of Kansas Irving Youngberg/Higuchi Endowment Research Award in Applied Sciences (1998)
- WSU President's Award for Distinguished Service (1998)
- WSU College of Engineering Award for Continuing Education (1996)
- AIAA Engineer of the Year Award – Wichita Section (1998)
- WSU Excellence in Research Award (1998)
- Kansas Academy of Science Distinguished Lecturer (1996)
- Ohio Aerospace Institute Distinguished Lecturer (1997)
- IEEE Award of Honor—St. Louis Section (1994)
- I.I.T. Kharagpur Distinguished Alumni Award (1994)
- AIAA Technical Achievement Award—St. Louis Section (1991)
- Listed in: *Who's Who in the Midwest, Who's Who in America, Who's Who in the World, American Men and Women of Science, Who's Who in American Education, International Who's Who of Professionals, Who's Who of Asian Americans, International Directory of Distinguished Scientists, Men of Achievement, etc.*